Magnet Needs for a Muon Collider

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Outline

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- Overview – key elements of a muon collider
- Magnet-related issues along the collider path
- Some magnet design paradigms to consider
  - Development & demonstration
  - Magnets for intermediate facilities & for final collider
- A review of key magnet-related challenges

Overview of a Muon Collider

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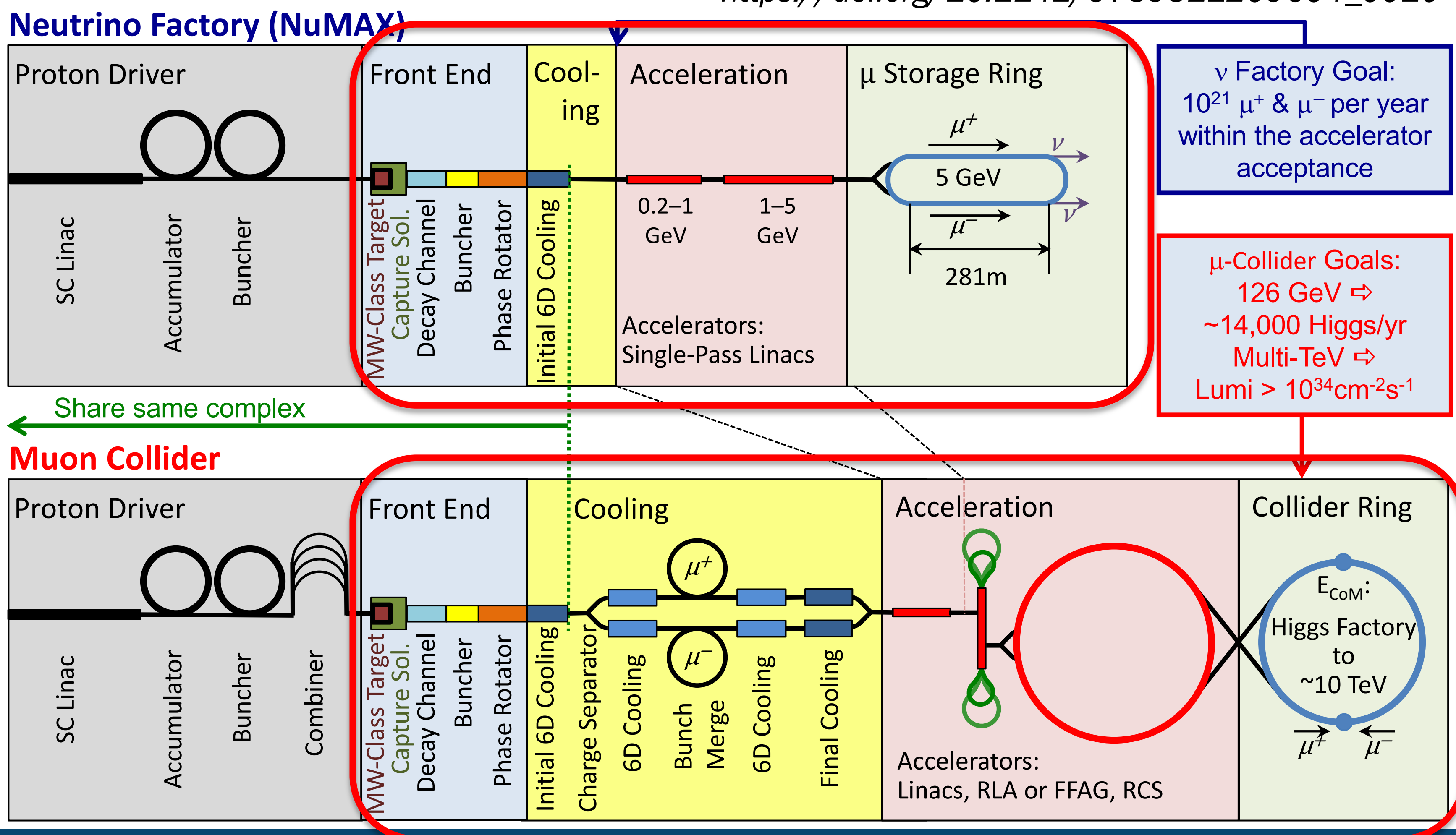
- Magnets are central to target & front end, cooling, acceleration, collider ring

Boscolo, Delahaye, Palmer
https://doi.org/10.1142/9789811209604_0010



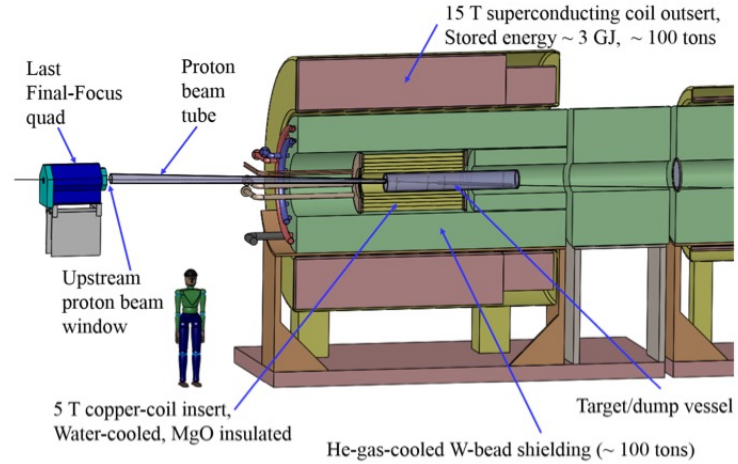
Key issues: Target/front end

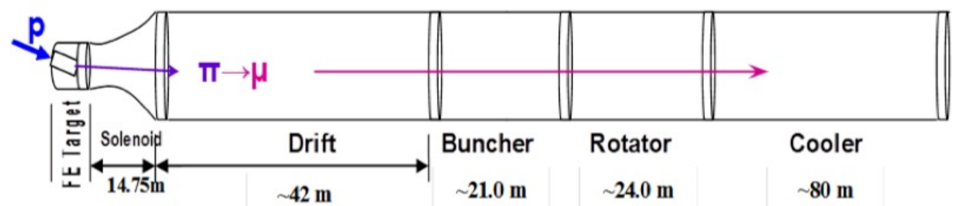
- High field target solenoid
- Tapered field capture solenoid

- Challenges:
  - ~20T solenoid field
  - High radiation environment
  - Likely inaccessible for hands-on maintenance
  - Large stored energy
  - Stray fields

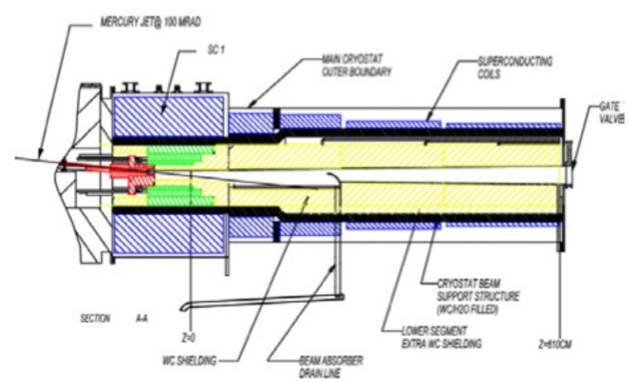
- Mitigations:
  - Optimize bore vs radiation load
    - e.g. Tungsten shielding?
  - CICC technology may be appropriate
  - Active shielding (if necessary)
  - Synergies with
    - NHMFL high field solenoids
    - FES central solenoid developments
      - But leverage DC nature of field

McDonald et al., IPAC2014





Neuffer et al., https://arxiv.org/pdf/1711.11120.pdf



Zisman, TAS VOL. 18, NO. 2, JUNE 2008

Technology options

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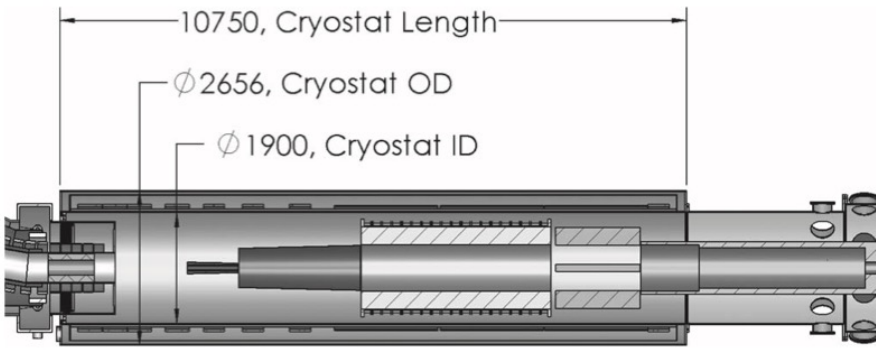
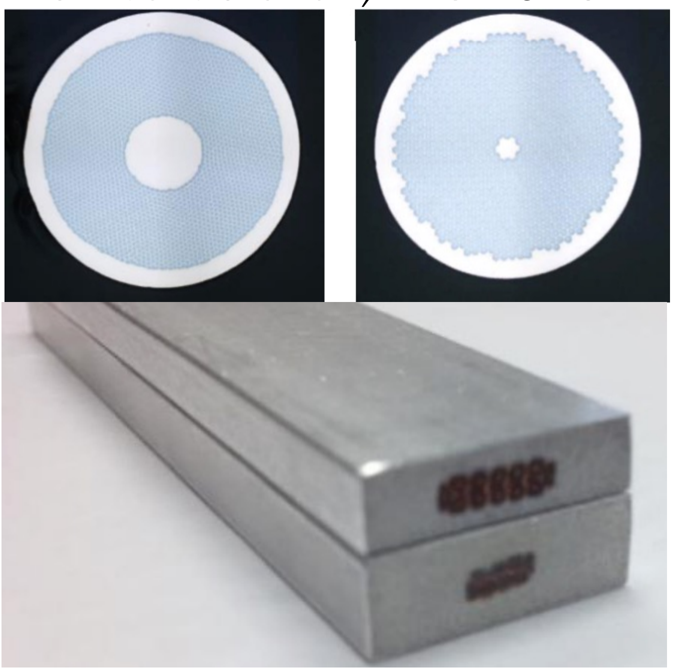


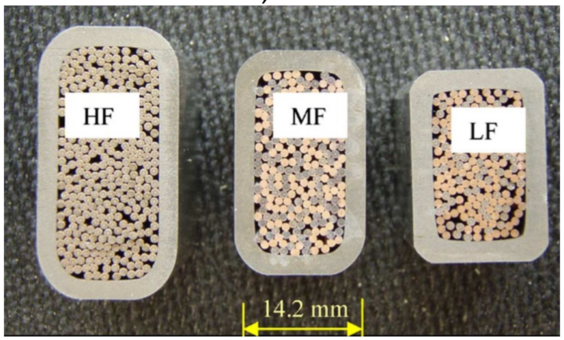
Ostojic et al., TAS 2013

Mu2e detector solenoid (2T, 2m ID)

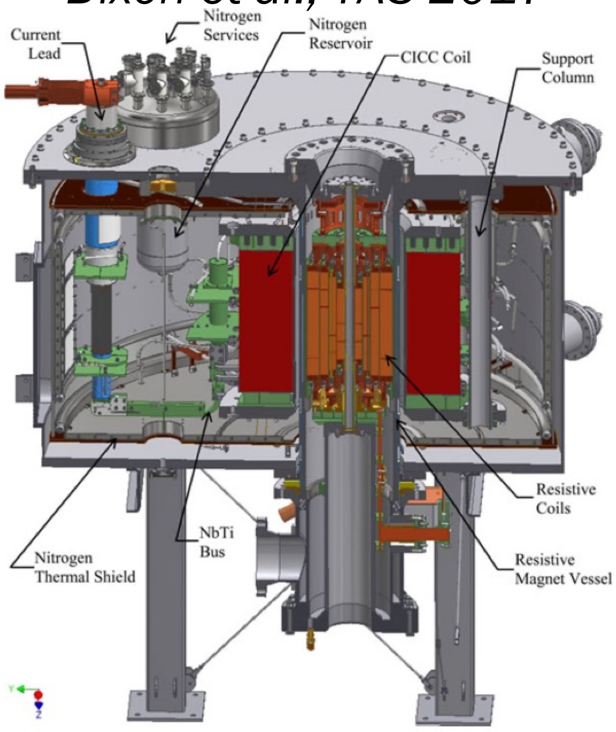
Lombardo et al., TAS 2016



Bird et al., TAS 2009



Dixon et al., TAS 2017

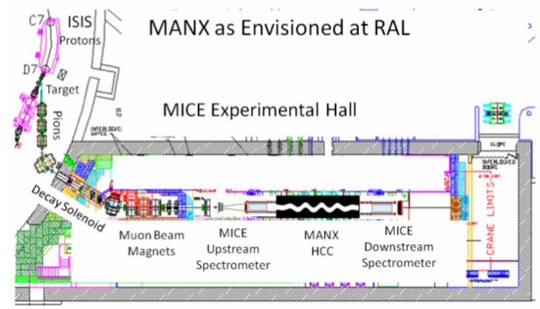


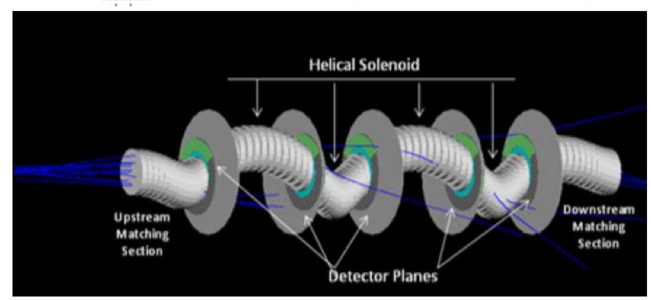
NHMFL Series connected hybrid Outsert: (~13T, 610mm ID)

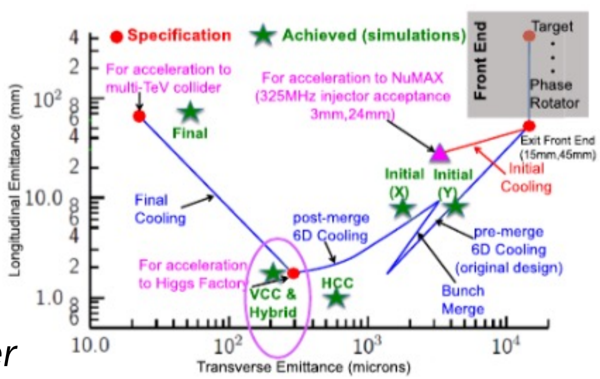
Key issues: Cooling

- Multiple cooling sections needed to reduce the beam phase space
  - Longitudinal =>large momentum-acceptance acceleration and storage
  - Transverse=>need rapid 4D (some 6D) cooling=>solenoids
  - For collider, need small energy spread=> final cooling
- Ionization cooling:
  - Requires strong solenoidal fields for focusing
  - Large bore to accommodate (room temp) absorbers and RF
- Challenges:
  - Requires HTS for fields >~20T
    - =>32T solenoid demonstration at NHMFL shows potential, but probably need to develop and demonstrate with HTS cable technology
  - Helical channel has significant structural complexities

Yonehara et al., PAC09







Boscolo, Delahaye, Palmer
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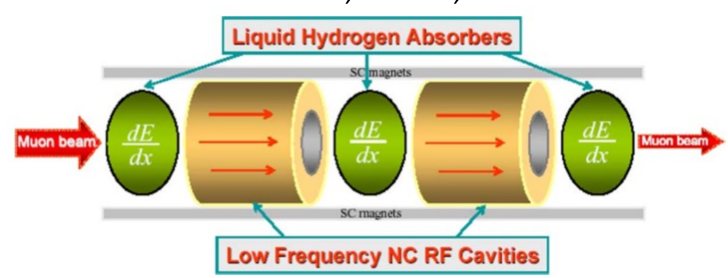
Zisman, TAS, 2008



Key issues: Acceleration

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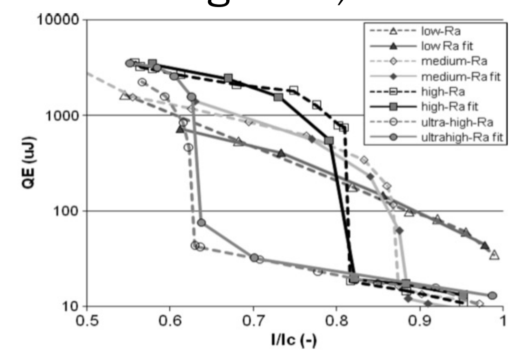
- Classic approach:
  - synchrotron-based – ramp magnets in concert with RF acceleration
  - Challenges:
    - dB/dt induces…
      - heat in conductor (AC losses); =>impacts performance $J \leq J_c(B,T)$
      - Magnetization in superconductor (=>field errors)
      - Eddy currents in associated conductive materials (=>field errors)
    - Fatigue considerations drive many design considerations
    - Cycle time drives collider performance
  - Mitigation approaches:
    - Laminations in all conducting materials (where possible)
    - Small filaments in superconductor
    - Reduce contact resistance between strands
  - Elements of the acceleration may use different paradigms, e.g.
    - Recirculating Linacs
    - FFAG or similar – the holy grail is to…
      - Eliminate ramping
      - Maximize muon momentum acceptance
      - Store beams of varying energies simultaneously

Volpini et al., TAS 2011

TABLE I
WIRE MAIN CHARACTERISTICS

Diameter after coating	0.825 ± 0.003		mm
Filament twist pitch	5 +0.5 -0		mm
Effective Filament Diameter	1st generation	≤ 3.5	μm
	2nd generation	≤ 2.5	μm
Interfilament matrix material	Cu-0.5 wt% Mn		
Filament twist direction	right handed (clockwise)		
Ic @ 5 T, 4.22 K	> 541		A
n-index @ 5 T, 4.22 K	> 30		
Stabilization matrix	Pure Cu		
ρ_t at 4.22 K	$0.4 + 0.09\,B$ [T]		nΩ·m
Cu+Cu-Mn : Nb-Ti ratio (α)	$>1.5 \pm 0.1$		
Surface coating material	Staybrite (Sn-5 wt% Ag)		

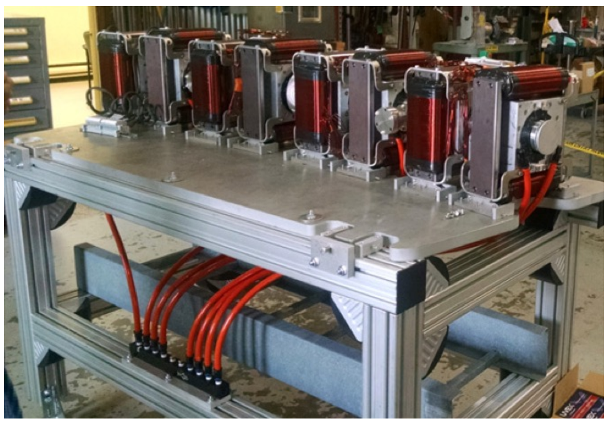
Willering et al., TAS 2008

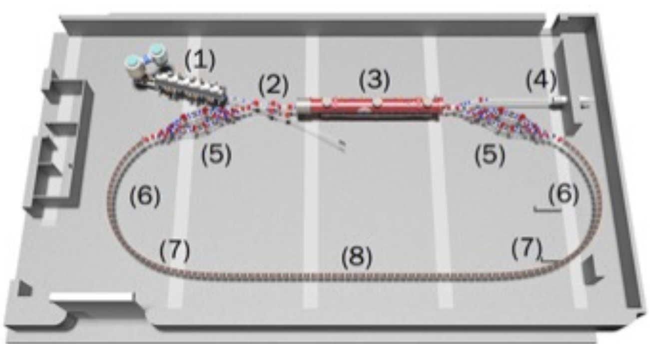


Non-ramping options are intriguing

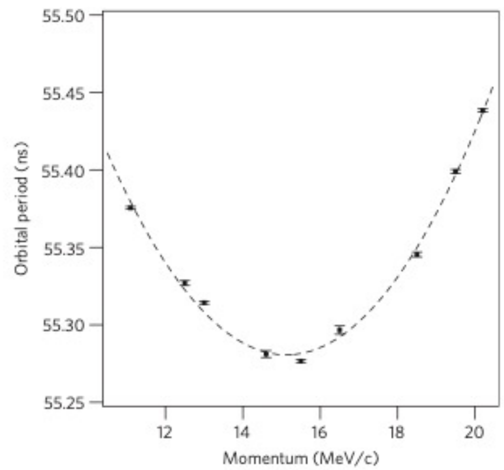
- Fixed field configurations – can they work?
- Non-scaling FFAG
    - o “built for Muons”

CBETA - Trbojevic et al., IPAC2017

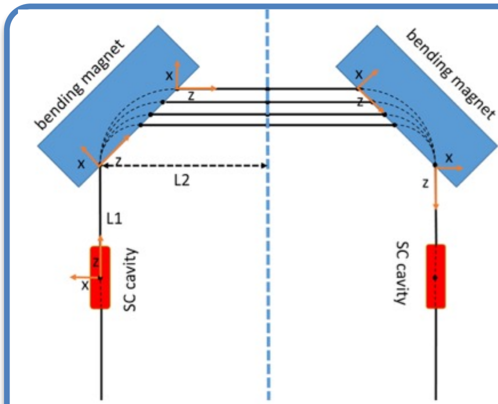


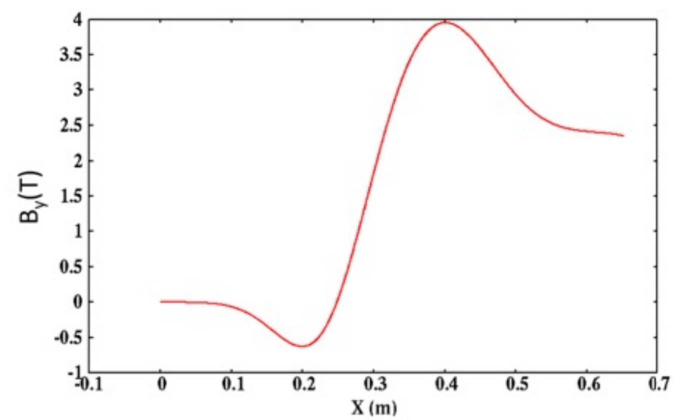


EMMA - Machida et al., Nature Physics, 2012



Qiang, Brouwer, Teyber, PRAB 2021





Key issues: Collider ring magnets

- Dipoles, quadrupoles for main ring
- Interaction region magnets

- Significant work has been done on ~1.5TeV muon collider ring concepts
- Major considerations:
  - Compact ring enables increased collision rates and hence physics

  =>Compact implies higher field dipole
  - Apertures of 5-sigma are considered acceptable
  - Significantly heat loads (SR, ***Muon decay***, Muon losses)

Collider dipole magnets

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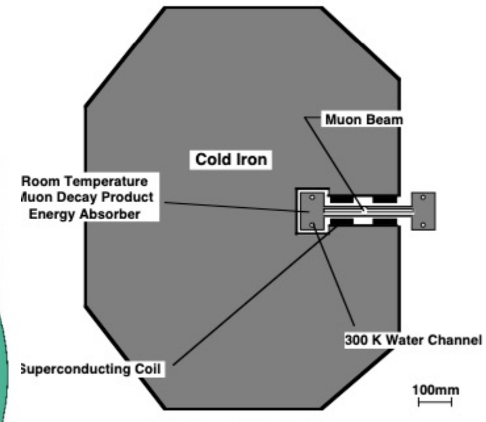
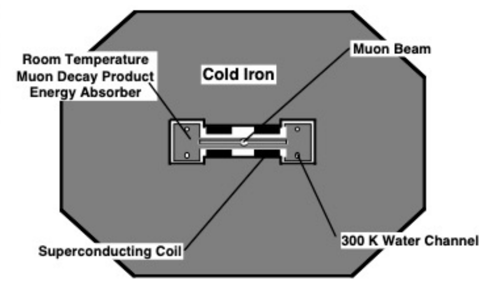
- Dipoles must address significant heat load as well as radiation load
  - ~~Open midplane~~ or shielding (e.g. Tungsten)
  - Example: 2TeV (4TeV c-m) study suggested 2kW/m deposition
  - ⇒ Must extract most heat at higher temperature in order to be feasible
- Challenge for high field magnets
  - Aperture is “costly” at high field

Note: ongoing work in the DOE-OHEP’s US Magnet Development Program is highly relevant

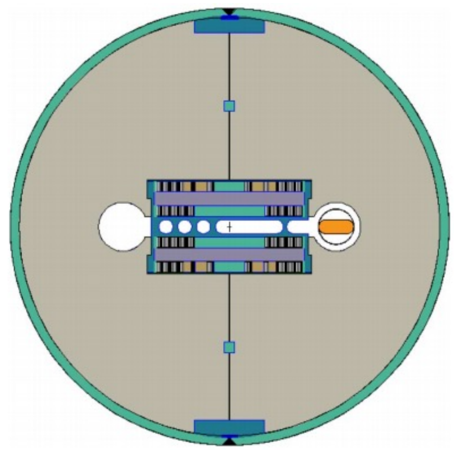
Muon collider feasibility study 1997, LBNL-38946



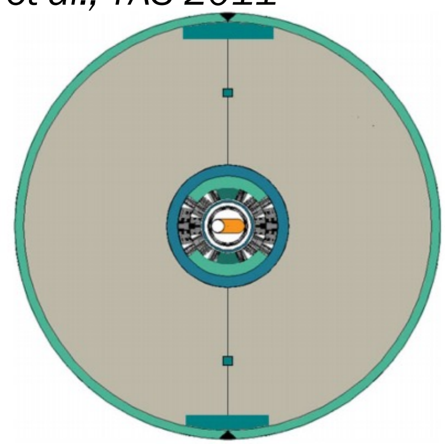
a) Cold Iron C Dipole Magnet

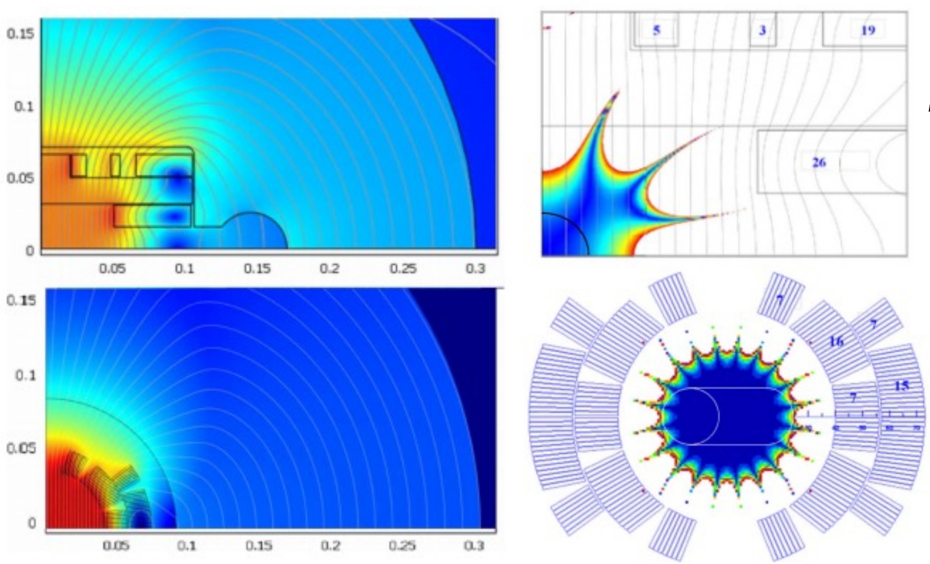


b) Cold Iron H Dipole Magnet



Novitski et al., TAS 2011





Interaction region magnets

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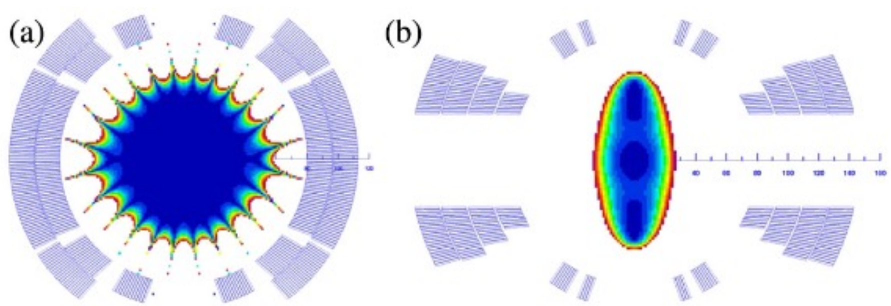
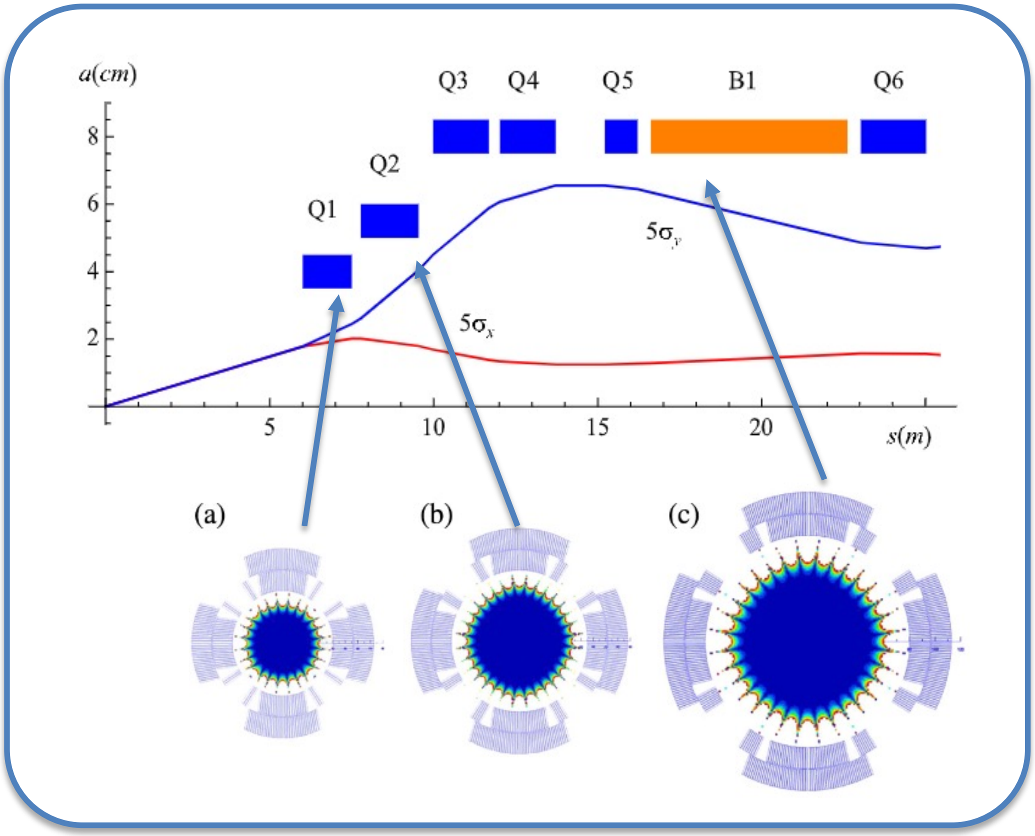
- IR quads operating at ~11-12T
  - Large bore (~150mm)
  - Parameters are similar to HL-LHC quads

Similar, but HL-LHC quads allow for a Tungsten shield!

- IR Dipoles
  - Need to tolerate high radiation
  - =>Large bore, or open midplane

Alexahin et al., PTSTAB 14,2011





Main research areas

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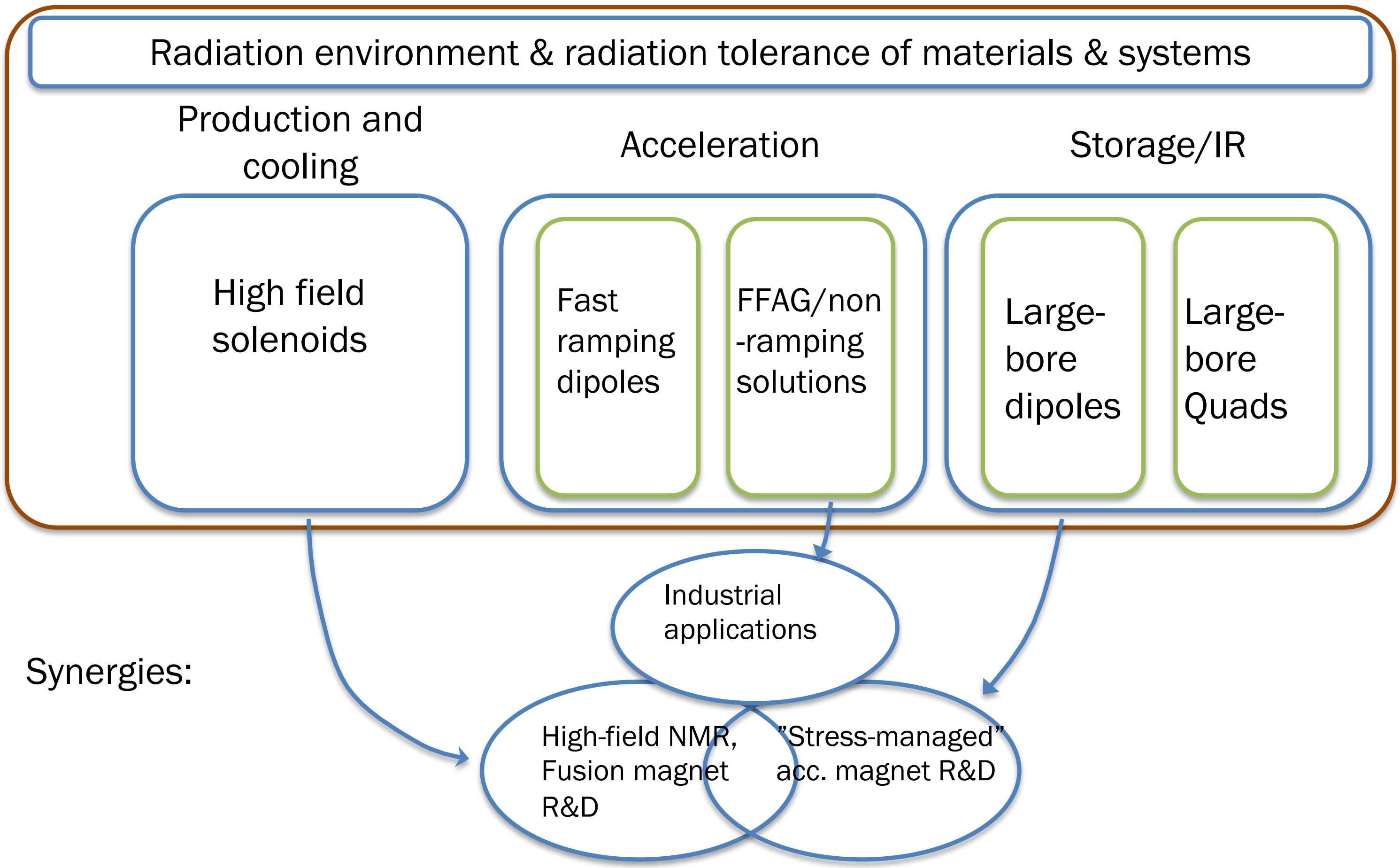

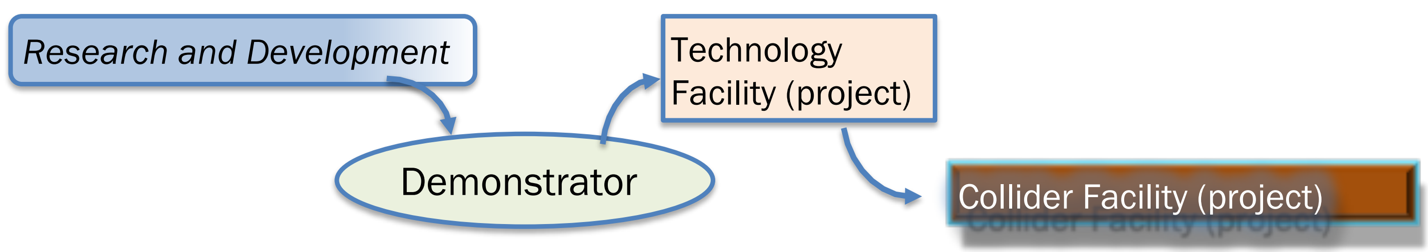

Ideas for a magnet technology roadmap

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- Core elements:
  - High-field solenoid development
  - Large bore dipole technologies
  - Fast-ramping dipoles – optimized in pulse duration, frequency, field
  - Understanding radiation environment and appropriate materials

- High-risk / high-reward element:
  - Non-ramping magnet/optics solutions for acceleration

Backup

Magnets start with the superconductor

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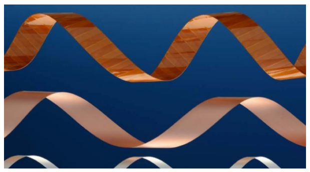
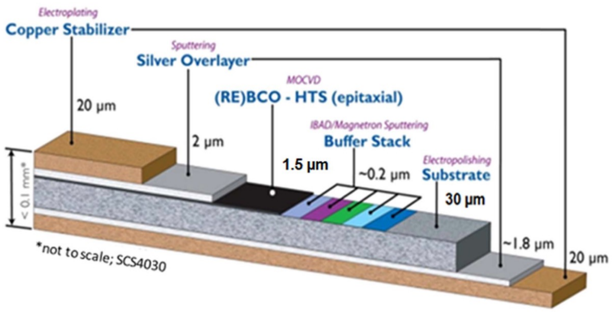
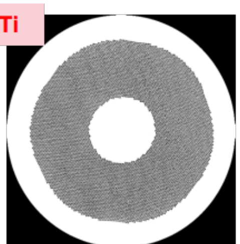
- We are about to put Nb_3Sn into a collider for the first time, and are investigating the potential of HTS



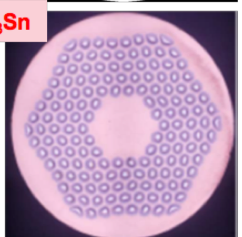
SuperPower Inc



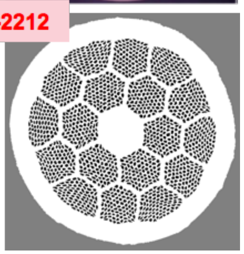
Nb-Ti

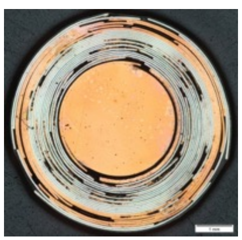


Nb_3Sn

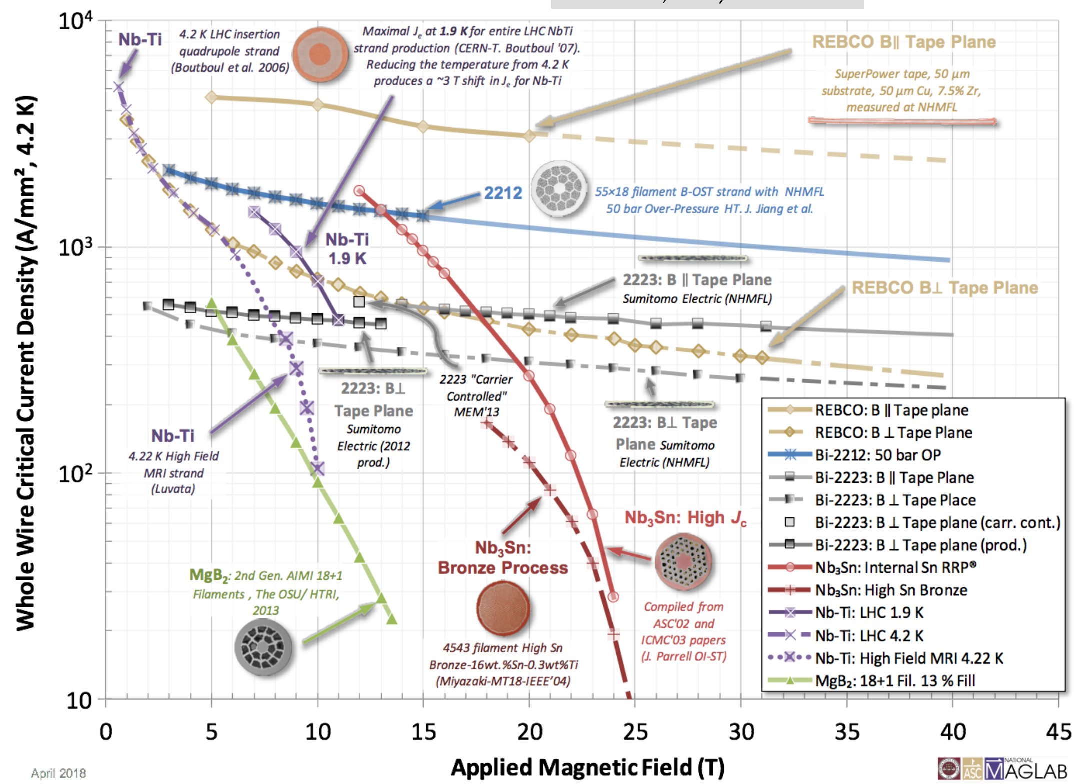


Bi-2212





Peter Lee, ASC/NHMFL



In the US, a collaboration is focused on magnet technology for future colliders

U.S. MAGNET DEVELOPMENT PROGRAM

The Updated Roadmap for MDP is publicly available
https://arxiv.org/abs/2011.09539

LBNL, FNAL, BNL, ASC/NHMFL

- **Major themes of the updated Roadmaps:**
  - ***Explore the potential for stress-managed structures*** to enable high-field accelerator magnets, i.e. structures that mitigate degradation to strain-sensitive Nb_3Sn and HTS superconductors in high-field environments;
  - ***Explore the potential for hybrid HTS/LTS magnets*** for cost-effective high field accelerator magnets that exceed the field strengths achievable with LTS materials;
  - ***Advance magnet science*** through the rapid development and deployment of unique diagnostics and modeling tools to inform and accelerate magnet design improvements;
  - ***Perform design studies*** on high field accelerator magnet concepts to inform DOE-OHEP on further promising avenues for magnet development;
  - ***Advance superconductors*** through enhanced performance, improved production quality, and reduction in cost - all critical elements for future collider applications.